

METHODS

Evaluation of Aortic Stenosis by Continuous Wave Doppler Ultrasound

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Twenty-four patients with suspected aortic stenosis (Group I) were evaluated noninvasively by continuous wave Doppler ultrasound before undergoing cardiac catheterization. Twenty normal subjects served as the control group (Group II). Maximal velocity measurements in the ascending aorta ranged from 3.0 to 5.8 m/s (mean 4.34 ± 0.65) in Group I versus 1.0 to 1.6 m/s (mean 1.28 ± 0.16) in Group II ($p < 0.001$). Using the Bernoulli equation, the peak pressure gradient across the aortic valve was calculated from the maximal velocity in the Group I patients.

The results correlated well with the peak aortic valve gradient obtained at cardiac catheterization ($r = 0.79$). In 20 of these 24 patients, the peak Doppler gradient was within 25% of the gradient found at cardiac catheterization. In three patients, the Doppler study under-

estimated the gradient by slightly more than 25% but still detected the presence of significant aortic stenosis. The Doppler technique failed to detect critical aortic stenosis in only one patient. Significant overestimation of the gradient by Doppler measurement did not occur in any patient. The technique was particularly helpful in older patients in whom other noninvasive tests often yield inconclusive results.

An important but infrequent limitation of the technique is underestimation of the gradient that occurs when the angle of incidence between the ultrasound beam and aortic blood flow is too large. The findings indicate that continuous wave Doppler ultrasound provides a reliable estimate of the valvular gradient in most patients with aortic stenosis.

The diagnosis of aortic stenosis and an accurate assessment of its hemodynamic severity may be difficult to determine solely on the basis of clinical findings (1,2). This is especially true in elderly patients in whom the quality and location of the murmur and the character of the carotid pulse may yield misleading information (3,4). The presence of left ventricular dysfunction and the coexistence of other valvular lesions are additional factors that may cause difficulty in estimating the degree of left ventricular outflow obstruction (1,5). Noninvasive studies utilizing echocardiography, phonocardiography and external carotid pulse recordings may provide useful information and can usually differentiate normal individuals from those with aortic stenosis (6-10). However, a major limitation is their inability to reliably distinguish patients with mild aortic stenosis from those with severe valvular obstruction (11).

Doppler ultrasound is a comparatively new noninvasive technique that permits the measurement of blood flow ve-

locity within the cardiac chambers and great vessels (12). Reports appeared recently (13,14) describing the value of pulsed Doppler echocardiography in the assessment of aortic stenosis. Although pulsed Doppler ultrasound has range resolution that permits the localization of flow disturbances, it is limited by its inability to measure high flow velocities. This is a major disadvantage in patients with aortic stenosis where high velocities are invariably present. Continuous wave Doppler ultrasound, though lacking range resolution, is capable of measuring the high velocity transvalvular flow that is present in aortic stenosis (12). The pressure gradient across a stenotic valve can be calculated from this measurement by the application of Bernoulli's principle (15-19).

This study was undertaken to further assess the reliability of continuous wave Doppler ultrasound as a noninvasive method of calculating the aortic valve pressure gradient in patients with aortic stenosis.

Methods

Patients. Forty-four patients divided into two groups comprised the patient population. Group I consisted of 24 consecutive patients with clinically suspected aortic stenosis who were referred for Doppler ultrasound studies and sub-

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sequently underwent diagnostic cardiac catheterization. Twelve patients were men and 12 were women ranging in age from 29 to 85 years (mean 66). Three patients (Cases 3, 16 and 19) had associated moderate aortic regurgitation and two patients (Cases 9 and 14) had associated severe aortic regurgitation. Other significant valvular lesions included mitral regurgitation in three patients and mitral stenosis in three patients. Significant coronary artery disease was present in 13 patients.

Group II consisted of 20 control patients. Twelve were men and eight were women ranging in age from 24 to 80 years (mean 49). Ten were normal healthy subjects without murmurs and a normal-appearing aortic valve on M-mode and two-dimensional echocardiographic examination. Ten patients underwent diagnostic cardiac catheterization for evaluation of chest pain. Seven patients had significant coronary artery lesions and three had normal coronary arteries. All 10 patients had a normal ejection fraction and no patient had a detectable gradient across the aortic valve.

Doppler ultrasound examination. *Instruments.* The Doppler ultrasound examinations were obtained with commercially available instruments. Patients 1 through 13 were examined with an independent Doppler instrument (PEDOF) interfaced with an Irex System II strip chart recorder. In Patients 14 through 24, the study was performed utilizing a phased array echocardiographic system with simultaneous pulsed and continuous wave Doppler (Irex System III). Doppler examinations may be done either simultaneously with the two-dimensional echocardiogram or with an independent Doppler transducer. The instruments used in this study have an ultrasonic frequency of 2 MHz and can be operated in either the pulsed or continuous mode. In the pulsed mode at depth settings of less than 9 cm, the repetition frequency is 8.62 KHz and velocities up to 1.7 m/s can be measured. At depth settings greater than 9 cm, the repetition frequency is 5.74 KHz and velocities up to 1.1 m/s can be measured. When operated in the continuous mode, velocities up to 6 m/s can be measured but with loss of range resolution.

The Doppler output signals include analog displays of the maximal and mean recorded velocities and an amplitude signal. The maximal velocity curve is used to measure blood flow velocity. The mean velocity curve, an instantaneous weighted average of all returning frequencies, is used to determine the direction of blood flow. A positive curve indicates flow toward the transducer and a negative curve indicates flow away from the transducer. The amplitude signal is related to the intensity of the reflected ultrasound beam. Reflection of sound from the valves is much stronger than that from the blood. Therefore, distinct spikes on the amplitude curve produced by opening and closing of the valves can be obtained.

The phased array Doppler system is also equipped with a chirp-Z spectral analyzer that displays the full spectrum of Doppler shifts and provides both the direction of flow

and a quantification of blood flow velocity. An audio signal corresponding to the frequency shifts along the sound beam is helpful in positioning the transducer. Maximal velocity measurements were made from the analog display in Patients 1 through 13 and from the spectral display in Patients 14 through 24.

Recording procedure. In performing the Doppler examination, it is important that the angle of incidence between the ultrasound beam and aortic blood flow be as close to zero degrees as possible. Because the direction of blood flow in the ascending aorta may vary from patient to patient, it was usually necessary to obtain recordings from multiple transducer positions. The examination was started with the patient in the supine position, the transducer at the suprasternal notch and the ultrasound beam directed inferiorly toward the aortic valve (Fig. 1, left). The transducer was tilted slowly until the highest frequency Doppler shifts could be obtained with the aid of the audio signal. Additional recordings were obtained with the patient in the right lateral decubitus position with the transducer in the first or second right intercostal space and from the apex or lower left sternal border with the patient in the left lateral decubitus position (Fig. 1, right).

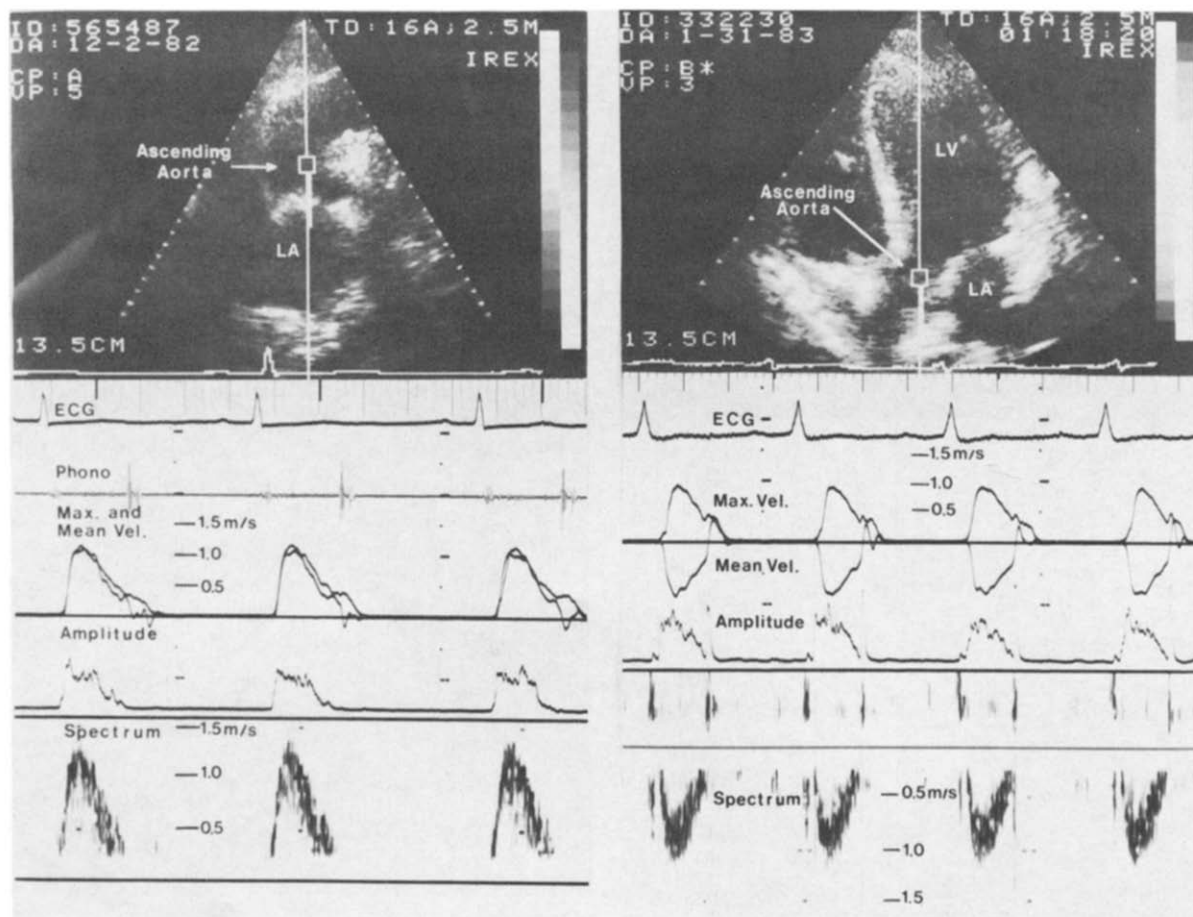
Two-dimensional echocardiography was helpful in directing the ultrasound beam toward the aortic valve and ascending aorta. However, the independent Doppler transducer can detect weaker signals than can the combined phased array two-dimensional Doppler transducer, and results of preliminary studies (20) show that peak velocities measured with the independent transducer are slightly higher than those measured with the combined system. Therefore, all velocity measurements reported in this study were obtained with the independent Doppler transducer using the audio signal to obtain the maximal Doppler shift. In aortic stenosis, the increased velocity across the aortic valve resulted in a clear high frequency audio signal that was easily distinguished from the audio signal of normal aortic flow.

Calculation of aortic pressure gradient. Using a method that has been described previously, the peak pressure gradient across the aortic valve was calculated from the maximal velocity recording by applying the formula (16)

$$\Delta P = 4 \times V_2^2,$$

where ΔP is the pressure gradient and V is the maximal velocity across the aortic valve in m/s. The peak pressure gradient calculated by this method was compared with the peak aortic valve pressure gradient at cardiac catheterization.

Cardiac catheterization. Diagnostic left heart catheterization was performed by the retrograde femoral artery technique. The time interval between the Doppler study and cardiac catheterization in Group I ranged from 1 day to 7 weeks (median 3 days). Twenty of these 24 Group I patients underwent catheterization within 2 weeks after the Doppler ultrasound examination. Catheterization in Group II was



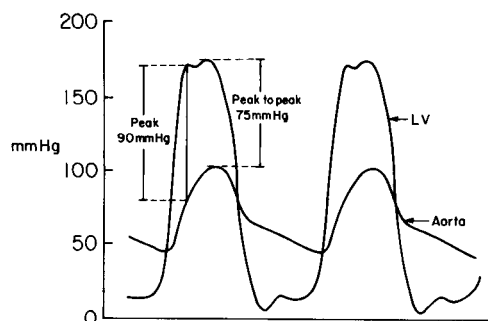
performed within 48 hours after the Doppler study. All patients remained in a clinically stable condition during the interval between the Doppler examination and cardiac catheterization.

The method used to measure the aortic valve pressure gradient was left to the discretion of the physician performing the catheterization. In 19 patients, the aortic valve gradient was measured from recordings of the left ventricular pressure and central aortic pressure obtained during pullback of the catheter across the aortic valve. In five patients, it was measured from simultaneous recordings of the left ventricular and femoral artery pressures. In this latter group, simultaneous femoral artery and central aortic pressures were recorded and were equal in three patients and differed by 3 and 5 mm Hg, respectively, in two patients. The peak to peak aortic valve pressure gradient was the difference between peak left ventricular systolic pressure and the peak aortic or femoral artery systolic pressure (Fig. 2). The peak aortic valve pressure gradient was the maximal pressure difference measured during systole between the left ventricle and the aorta or femoral artery.

Technically adequate left ventriculograms performed in the right anterior oblique projection were available in 20 of the 24 Group I patients with suspected aortic stenosis. The ejection fraction in these patients ranged from 46 to 81%.

Figure 1. Left, Two-dimensional echocardiogram and Doppler ultrasound recording obtained with the transducer in the suprasternal notch. Note that the direction of flow in the ascending aorta as shown on the mean velocity (Vel.) tracing and spectrum is toward the transducer. The maximal (Max.) velocity is 1.3 m/s. Right, Similar study with the transducer at the apex showing the direction of flow in the ascending aorta away from the transducer and a maximal velocity of 1.1 m/s. ECG = electrocardiogram, LA = left atrium, LV = left ventricle, Phono = phonocardiogram.

Figure 2. Left ventricular (LV) and aortic pressure tracing in a patient with aortic stenosis demonstrating measurement of peak and peak to peak pressure gradients.



Statistical analysis. Statistical analysis was performed using the paired and unpaired *t* test. Data are expressed as mean \pm standard deviation. The peak pressure gradients obtained by Doppler measurement and cardiac catheterization were compared using linear regression analysis.

Results

Maximal blood flow velocity. In the 20 control subjects (Group II), maximal blood flow velocity in the ascending aorta was recorded equally well from the suprasternal notch and cardiac apex. In the 24 patients with suspected aortic stenosis (Group I), the transducer position from which the highest velocities were recorded varied considerably (Table 1). In 14 patients, turning the patient to the right lateral decubitus position and placing the transducer along the upper right sternal border yielded the highest recorded velocities. In the remaining patients, the maximal velocity was best recorded from the lower left sternal border in five patients, cardiac apex in three patients and suprasternal notch in two patients. Maximal velocity in the control group ranged from 1.0 to 1.6 m/s (mean 1.28 ± 0.16) compared with 3.0 to 5.8 m/s (mean 4.34 ± 0.65) in the group with aortic stenosis (probability [*p*] < 0.001).

In those patients with suspected aortic stenosis, the maximal velocity measurements were used to calculate the peak aortic pressure gradient. Representative Doppler studies with the transducer at the second right intercostal space and cardiac apex are illustrated in Figures 3 and 4.

Aortic valve gradient. Aortic valve gradients calculated by Doppler study and those measured at cardiac catheterization are listed in Table 1. The average peak systolic gradient obtained at cardiac catheterization was 91 ± 27 mm Hg compared with a peak to peak gradient of 69 ± 22 mm Hg (*p* < 0.001). There was a good correlation between peak aortic valve gradients obtained by continuous wave Doppler and those measured at cardiac catheterization (Fig 5) (*r* = 0.79). In 20 of the 24 Group I patients, the peak gradient calculated from the Doppler study was within 25% of the peak gradient found at cardiac catheterization. In three patients (Cases 13, 14, 21) the Doppler study underestimated the gradient by slightly more than 25% but was still able to detect the presence of significant aortic stenosis. The Doppler technique failed to detect the presence of significant valvular stenosis in only one patient (Case 6). In Patients 6 and 13, the clear high frequency audio signal characteristic of aortic stenosis could not be recorded despite the use of multiple transducer positions. Many low frequency sounds were present indicating that the angle between the ultrasound

Table 1. Catheterization and Doppler Ultrasound Data in 24 Patients With Suspected Aortic Stenosis

Case	Age (yr) & Sex	Transducer Position*	Doppler Ultrasound Data		Catheterization Data	
			Maximal Velocity (m/s)	Peak Pressure Gradient (mm Hg)	Peak Pressure Gradient (mm Hg)	Peak to Peak Gradient (mm Hg)
1	35F	SSN	4.8	92	110	100
2	78F	RSB	4.2	71	60	45
3	55M	RSB	4.1	67	80	70
4	72F	RSB	4.7	88	90	75
5	64M	RSB	5.8	135	180	130
6	68M	RSB	3.0	36	100	85
7	56M	RSB	3.8	58	63	50
8	61F	RSB	5.5	121	120	100
9	54F	LSB	4.2	71	65	50
10	81M	LSB	4.4	78	95	65
11	79F	Apex	3.4	46	50	40
12	59M	LSB	4.8	92	95	80
13	62F	RSB	3.8	58	90	75
14	80M	RSB	4.0	64	90	52
15	85F	RSB	4.0	64	75	50
16	71M	Apex	4.5	81	78	60
17	29F	RSB	4.7	88	92	77
18	74M	RSB	3.9	61	62	47
19	74F	LSB	3.8	58	70	50
20	55M	SSN	4.8	92	95	80
21	74F	Apex	3.8	58	82	55
22	74M	RSB	5.0	100	120	70
23	74M	RSB	4.3	74	85	65
24	72F	LSB	5.0	100	125	95

*Position from which highest velocity was recorded. LSB = lower left sternal border, RSB = upper right sternal border, SSN = suprasternal notch.

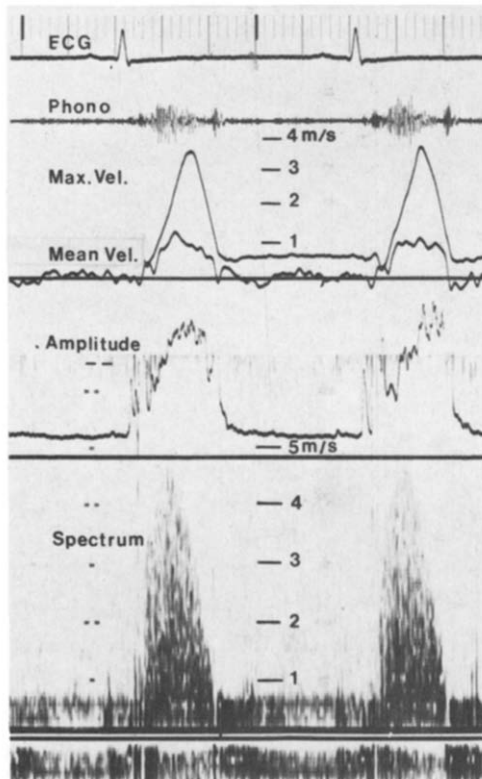


Figure 3. Case 17. Doppler study obtained from second right intercostal space. The direction of the aortic jet is toward the transducer as shown on the mean velocity (Vel.) tracing and the spectrum. The maximal (Max.) velocity as shown on the spectral display is 4.7 m/s and the calculated peak aortic valve gradient 88 mm Hg.

beam and the aortic jet was not small enough to obtain the maximal Doppler shift, thereby underestimating the severity of obstruction. In no case did the Doppler technique result in a calculated gradient significantly greater than that found at cardiac catheterization.

Discussion

Value of Doppler recording in assessment of aortic stenosis. The use of continuous wave Doppler ultrasound to measure valvular gradients was first reported in 1976 by Holen et al. (15). They demonstrated that the pressure gradient across a stenotic valve could be determined noninvasively using velocity measurements obtained by Doppler ultrasound techniques. Subsequent studies by Hatle et al. (16) verified these observations in mitral stenosis and extended them to include patients with aortic stenosis (17). By applying a formula based on Bernoulli's principle, these investigators were able to measure the pressure gradient in patients with valvular obstruction.

The present study provides additional evidence that Doppler ultrasound is a valuable noninvasive technique in the

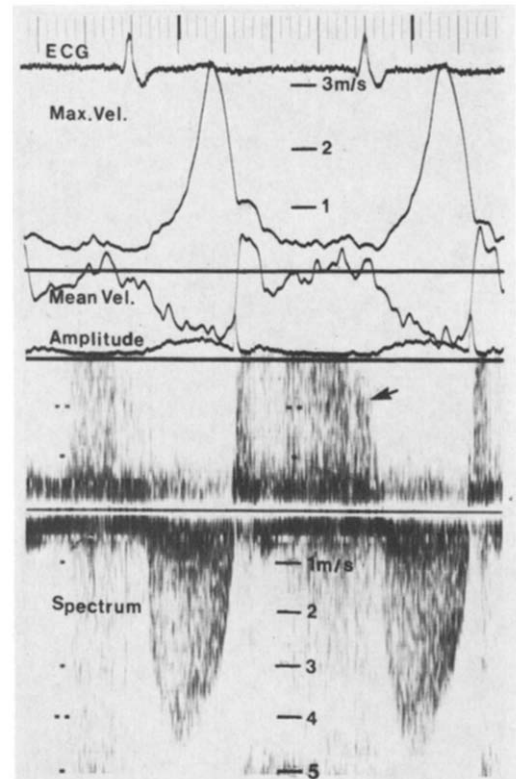
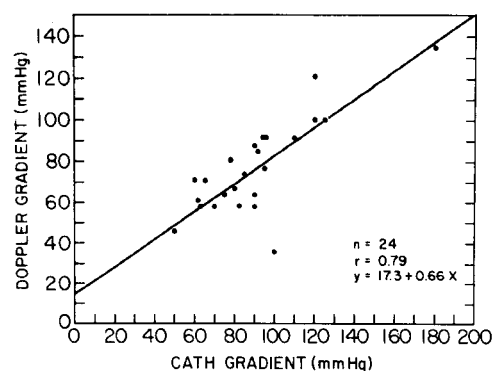


Figure 4. Case 16. Doppler study obtained from cardiac apex. The direction of the aortic jet is away from the transducer. The maximal velocity (Max. Vel.) as shown on the spectral display is 4.5 m/s and the calculated peak aortic valve gradient 81 mm Hg. During diastole flow toward the transducer (arrow) is present because of aortic regurgitation.

assessment of patients with suspected aortic stenosis. In the groups we studied, maximal velocity measurements recorded from the ascending aorta were useful to distinguish patients with aortic stenosis from normal subjects. The peak aortic valve gradient obtained by the Doppler technique was

Figure 5. Peak aortic valve gradient obtained by continuous wave Doppler ultrasound compared with that measured at cardiac catheterization (CATH) in 24 patients in Group I (patients with suspected aortic stenosis). The correlation coefficient (r) = 0.79.



compared with the peak gradient recorded at cardiac catheterization (Fig 2). This measurement, which represents the maximal systolic pressure difference between the left ventricle and the aorta, is generally higher than the peak to peak gradient commonly recorded at cardiac catheterization.

In those patients with suspected aortic stenosis, the peak pressure gradient calculated from maximal velocity measurements correlated well with the findings at cardiac catheterization. In four patients, the gradient was substantially underestimated. Doppler ultrasound failed to detect the presence of significant aortic stenosis in only one patient.

Causes of inaccurate Doppler studies. Underestimation of the aortic valve gradient results from failure to obtain a small enough angle of incidence between the ultrasound beam and aortic blood flow. For example, an angle of incidence of 20° will underestimate the maximal velocity by 6%, which is a relatively small error. However, the pressure gradient is calculated by squaring the maximal velocity and, therefore, errors in angulation become magnified and may lead to significant underestimation. Despite this, no attempt was made to correct for the angle of incidence. Even when the two-dimensional echocardiogram shows the ultrasound beam to be parallel to the ascending aorta, the best Doppler signal may not be obtained. This is because the main jet of blood that flows through the stenotic valve may not be in a plane parallel to the ascending aorta or may be anterior or posterior to the ultrasound beam. Other factors that may preclude obtaining a satisfactory study include poor penetration of the ultrasound beam due to interposed lung tissue and an unusual chest wall configuration.

Significant overestimation of the aortic valve gradient did not occur in any of our patients, results similar to those of Hatle et al (17). Only 4 of 24 patients were found to have a greater peak gradient on Doppler study than found at the time of cardiac catheterization and these were minimal differences, ranging from 1 to 11 mm Hg. Because the studies were not performed simultaneously, small differences in stroke volume may account for these discrepancies.

Doppler studies in the elderly. Many of the noninvasive tests used in the diagnosis of aortic stenosis are less reliable in the elderly (3). In this group of patients, the characteristic slow rate of rise of the carotid upstroke may be masked by the widened pulse pressure that occurs as a result of decreased vascular compliance (4). Evaluation by M-mode (21) or two-dimensional (9) echocardiography may also be more difficult because heavy valvular calcification may result in multiple dense echoes that interfere with leaflet identification. Hatle et al (17) found that Doppler signals from the aortic jet in elderly patients were often difficult to record, leading to underestimation of the aortic valve gradient. This was attributed to greater variation in jet direction resulting from increased valve deformity and calcification. In the current study, the average age of the 24 patients with suspected aortic stenosis was 66 years and 17 of the patients

were older than 60 years. With one exception, all of the patients in this age group with significant aortic stenosis were identified. The explanation for the difference between our results and those of Hatle et al is unclear.

Effect of left ventricular dysfunction on assessment of aortic stenosis. Noninvasive assessment of aortic stenosis may also be difficult in the presence of left ventricular dysfunction. The left ventricular ejection time, which is usually prolonged in patients with critical aortic stenosis, may normalize in the presence of left ventricular failure. An echocardiographic technique using the constant wall stress hypothesis has been employed to estimate aortic valve gradients noninvasively (6). This technique is useful when left ventricular systolic function is normal, but in the presence of left ventricular failure, there is significant underestimation of the gradient. In our study, severe left ventricular dysfunction was not present in any of the patients, therefore, additional studies are needed to assess the ability of continuous wave Doppler ultrasound to measure the aortic valve gradient in the presence of marked left ventricular dysfunction.

Limitations of study. Certain limitations of this study should be mentioned. Maximal velocity measurements were obtained from the analog display in Patients 1 through 13 and from the spectral display in Patients 14 through 24. Results of one recent preliminary study performed in open chest dogs (22) show inaccurate detection of maximal velocity Doppler signals by the analog output. However, other investigators (17,18,23) found the analog output to be quite accurate in estimating pressure gradients in mitral stenosis and subvalvular and valvular aortic stenosis. In another study of 16 patients with pulmonary stenosis (24), maximal velocities measured by both spectral and analog displays were within 10% of each other in the vast majority of patients. Comparative data were not obtained in the present study.

Doppler and catheterization gradients were not obtained simultaneously in this study. None of the patients had any change in their clinical status but differences in stroke volume at the time of the respective studies could have caused a change in the measured gradients.

Locating the aortic jet with the independent transducer without the benefit of concomitant two-dimensional imaging was not a problem. The end of the independent transducer is angled and its diameter relatively smaller, making it easier to position in the suprasternal notch and narrow intercostal spaces than the larger two-dimensional transducer. Use of the amplitude curve to identify opening and closing of the aortic valve and the audio signal to locate the highest frequency Doppler shifts allowed us to obtain optimal recordings.

Clinical implications. The results of this study add further support for continuous wave Doppler ultrasound as a reliable method of estimating the valvular pressure gradient in patients with aortic stenosis. Of course, aortic valve area provides a better assessment of the severity of stenosis than

the pressure gradient, which is affected by the inotropic and chronotropic state of the myocardium. However, given a relatively normal myocardium, the aortic valve gradient provides a good estimation of the severity of valvular stenosis and can identify those patients in whom further invasive evaluation is indicated. Doppler ultrasound is particularly useful in the elderly in whom other noninvasive tests may yield inconclusive results. Though overestimation of the gradient is not a significant problem, underestimation may occur when the angle of incidence between the ultrasound beam and the direction of blood flow is too large. Despite this problem, we believe that the use of continuous wave Doppler ultrasound is a major addition to the noninvasive evaluation of patients with aortic stenosis.

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